

Proton superconductivity and the masses of neutron stars

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The unexpected temperature evolution of the neutron star in the Cassiopeia A supernova remnant (Cas A, for short) has renewed tremendous interest in the cooling mechanisms of neutron stars. In particular, the formation of superconducting protons and superfluid neutrons deep inside the cores of neutron stars have become focal points of the discussion. The purpose of this letter is to add a new aspect to this discussion, which focuses on the connection between proton superconductivity and the masses of neutron stars.

Assuming (as is currently the case) that the temperature evolution of Cas A is largely controlled by superconducting protons, we study a series of phenomenological proton-pairing models to determine how deep into the stellar core superconducting protons actually penetrate. This allows us to establish a heretofore unknown relationship between the mass of the neutron star in Cas A and the penetration depth of the superconducting proton phase. This relationship can be used to either predict the depth of the superconducting proton phase, or, conversely, determine the mass of Cas A from a reliable calculation of the size of the proton superconducting phase in superdense neutron star matter. We emphasize that the strategy outlined in this paper can be applied to any other neutron star of similar age, whose temperature might be reliably monitored over a several years period. High-mass neutron stars, such as the recently discovered neutron stars J1614-2230 ($1.97 \pm 0.04 M_{\odot}$) and J0348+0432 ($2.01 \pm 0.04 M_{\odot}$), appear particularly appealing as a significant fraction of the protons in their cores may be superconducting.

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Introduction. One of the most prominent ways of probing the poorly known core compositions and inner structures of neutron stars consists in studying the thermal evolution of such objects theoretically [1–23] and then comparing the outcome with the ever-increasing body of observed data on neutron star temperatures [4, 5, 10, 11, 24]. The quality of observed neutron star temperatures has culminated in the recent temperature data obtained for the compact object in the supernova remnant Cassiopeia A over a 10-year period [24]. The observed temperature evolution of Cas A exhibited a steeper temperature drop than originally thought possible for a star of that age (~ 300 years). Recent independent studies have shown, however, that the observed behavior can be explained if the protons form a 1S_0 superconductor with a pairing gap that is large and non-vanishing throughout the entire stellar core, and the neutrons in the core form a 3P_2 superfluid with a critical temperature of 5×10^9 K [10, 11]. The relatively

sharp decline of the temperature of Cas A is then caused by the emission of neutrinos from neutron pair-breaking-formation processes [10, 11]. It has also been shown that in-medium effects play a very important role for the temperature evolution of the neutron star in Cas A [25], and that the late onset of the direct Urca process, driven by the changing core compression during stellar spin-down, may provide an explanation of the observed data as well [26].

Building on earlier work [10, 11], here we too assume that the neutrons in the core of the neutron star in Cas A have formed a 3P_2 neutron superfluid. In contrast to the aforementioned work, however, we treat proton pairing in neutron stars [27] on a more general footing by considering a variety of different proton superconducting profiles and critical temperatures. As shown in this letter, this allows us to establish an important constraint on the core density (core penetration depth) up to which protons need to be superconducting so that agreement with the temperature data of Cas A is achieved. As in [10, 11] we assume that the protons in the stellar core are paired in the 1S_0 state since the first moments of the star’s evolution, which implies a critical temperature of $\sim 10^9\text{--}10^7$ K for proton superconductivity. The proton pairing is necessary as it suppresses both the (density dependent) di-

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rect Urca process among nucleons, $n \rightarrow p + e + \bar{\nu}_e$, as well as the modified Urca process, $n + n \rightarrow n + p + e + \bar{\nu}_e$, which would otherwise spoil the agreement with the Cas A data.

Proton Superconductivity Depth. We assume that the matter in the core of a neutron star is well described by the Akmal-Pandharipande-Ravenhall (APR) model for the nuclear equation of state [28, 29]. We shall use a parametrized version of this equation of state, as described in [29]. The choice of parameters used in our study is the same as in [26], such that the direct Urca process is allowed for stars with masses greater than $1.4 M_\odot$. Following [10, 11] we allow the neutrons in the core of the neutron star to form pairs in spin-triplet states (3P_2). As discussed in [11] neutrons in the crust are likely to form spin-singlet (1S_0) pairs, but these have little effect on the thermal evolution. For the neutron triplet pairs in the core we use a phenomenological model, as described in [44]. The values of the superfluid gap, suppression factors for neutrino emissivities, and the luminosity of the pair-breaking-formation processes were also taken from [44].

To determine how deep superconducting protons actually penetrate into the core of the neutron star in Cas A, we start our cooling simulations for a superconducting proton phase that penetrates deeply into the center of star. i.e. in this case all the protons are paired and have a very high critical temperature, meaning that the star begins its thermal evolution with all protons paired up. As already known from the work of [10, 11], this assumption leads to an agreement with the temperature data observed for Cas A. We then repeat the cooling simulation, but for incrementally reduced depths of the proton superconducting phase. This scheme is repeated until agreement with the Cas A temperatures is no longer achieved. The cooling simulations are carried out for neutron stars with masses of $1.4 M_\odot$, $1.6 M_\odot$, $1.7 M_\odot$, and $1.8 M_\odot$. As in [10], all our cooling simulations are for an accreted neutron star envelope. The value chosen for the accreted mass is $\Delta M/M = 5.5 \times 10^{-13}$.

In Fig. 1, we shown the temperature evolutions for our sample neutron stars, each one possessing a superconducting proton core of proper size so that agreement with the Cas A data is achieved. The insert in the upper right corner is an enlargements of the temperature data of Cas A observe over a 10-year time period. Also show in Fig. 1 is the temperature evolution of a $1.8 M_\odot$ neutron star when all neutrons and protons in the core are unpaired. The latter badly fails to describe the Cas A data.

Figure 2 displays the critical temperatures of superconducting protons for the neutron stars shown in Fig. 1. Their central densities can be read off from the termination points of each curve. Figure 3 shows the density dependence of the 1S_0 proton pairing gap for each stellar model. This figure shows that the depth of the superconducting proton phase increases with neutron star mass. This is a consequence of the direct Urca

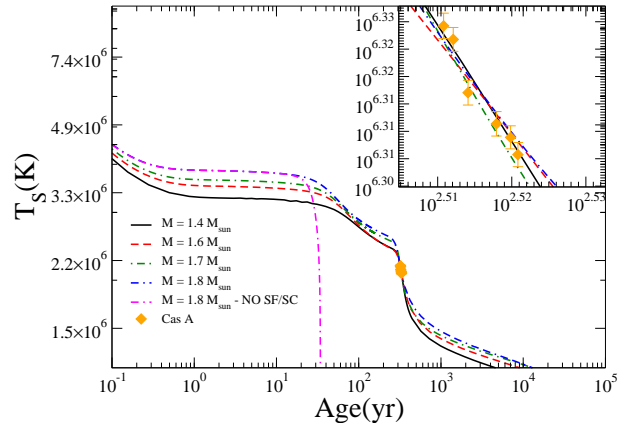


FIG. 1: (Color online) Thermal evolution of neutron stars with different gravitational masses. The proton superconductivity depth inside of each star has been chosen such that agreement with the Cas A data is achieved. (See text for more details.)

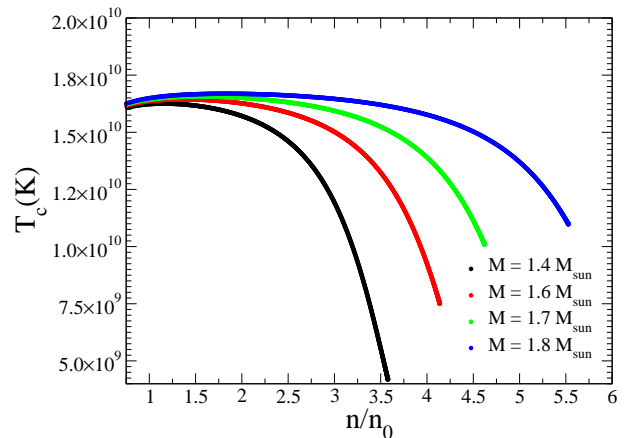


FIG. 2: (Color online) Critical temperatures, T_c , of superconducting 1S_0 protons as a function of baryon number density, n , for the stellar models of Fig. 1. ($n_0 = 0.16 \text{ fm}^{-3}$ denotes the baryon number density of ordinary nuclear matter.)

process, whose fast cooling rate needs to be suppressed by the superconducting protons. Otherwise the stellar model would cool down much faster than observed for Cas A. Aside from the direct Urca process, superconducting protons are also essential for controlling the changes in the stellar temperature caused by the modified Urca process. If it were not for the superconducting protons, the core temperature would drop too quickly so that a conflict with the emission of neutrinos from superfluid pair-breaking neutrons would arise, again rendering agreement with the Cas A data impossible. In summary, we conclude that, in agreement with [10, 11],

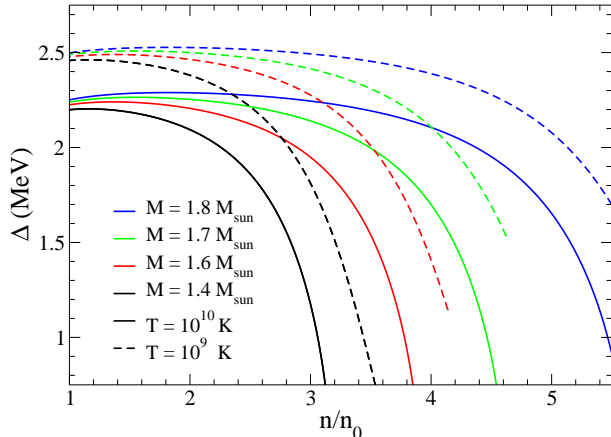


FIG. 3: (Color online) Gaps of superconducting 1S_0 protons for the neutron star models shown in Fig. 2. Solid lines denote a temperature of 10^{10} K, dashed lines correspond to a temperature of 10^9 K.

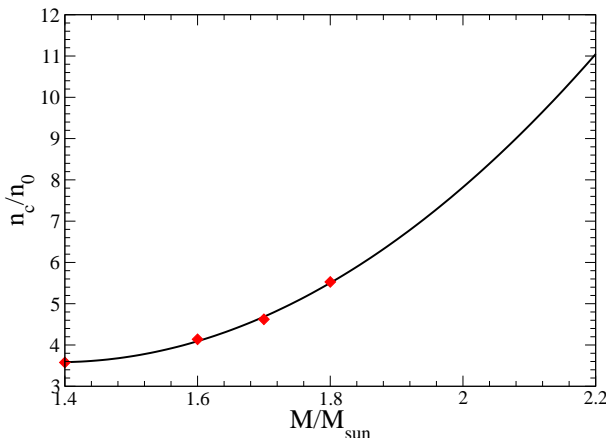


FIG. 4: (Color online) Proton superconductivity depth as a function of neutron star mass. The solid line represents the best (2nd order) polynomial fit of the data.

proton superconductivity needs to be present in the core of the neutron star in Cas A. Agreement with the observed temperatures of this object can however be achieved for a range of different proton superconducting profiles and critical temperatures. The latter allows us to establish a connection between the mass of a neutron star and the core penetration depth of superconducting protons.

The result is shown in Fig. 4, where we plot the density (core penetration depth) up to which superconducting protons exist in the core of Cas A, considering a range of possible stellar mass. The solid line represents a 2nd order polynomial best fit to the numerical data. One sees that for lower stellar masses the curve flattens considerably, approaching a penetration depth of $\rho_c/\rho_0 \simeq 3.75$ for a canonical neutron star mass of $1.4 M_\odot$. The flattening is consistent with the fact that for low stellar masses the direct Urca process is highly suppressed due to low proton fractions inside of such stars. Hence, the superconducting protons only need to suppress the modified Urca process along with other less rapid stellar cooling processes. This relationship shown in Fig. 4 can be used to either predict the depth of the superconducting proton phase, or, conversely, determine the mass of Cas A from a reliable calculation of the size of the proton superconducting phase in superdense neutron star matter.

Summary and Conclusions In this letter, we have thoroughly investigated the role of proton superconductivity for the cooling of neutron stars, building on earlier work of [10, 11]. Our results confirm that superconducting protons are required in order to explain the recent temperature data observed for Cas A. Furthermore our results agree with the maximum critical temperature for superfluid 3P_2 neutron established in [10, 11].

In contrast to earlier work, however, we study a series of phenomenological proton-pairing models to determine how deep into the stellar core superconducting protons actually penetrate. This allows us to establish a heretofore unknown relationship between the mass of the neutron star in Cas A and the penetration depth of the superconducting proton phase. This relationship can be used to either predict the depth of the superconducting proton phase, or, conversely, determine the mass of Cas A from a reliable calculation of the size of the proton superconducting phase in superdense neutron star matter. We emphasize that the strategy outlined in this paper can be applied to any other neutron star of similar age, whose temperature has been reliably monitored over a several years period. High-mass neutron stars, such as the recently discovered neutron stars J1614-2230 ($1.97 \pm 0.04 M_\odot$) [53] and J0348+0432 ($2.01 \pm 0.04 M_\odot$) [54], appear particularly appealing as a significant fraction of the protons in their cores may be superconducting.

This research clearly underlines the need for improved, state-of-the-art calculations focusing on the role of protons (as well as neutrons) in superdense neutron star matter.

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